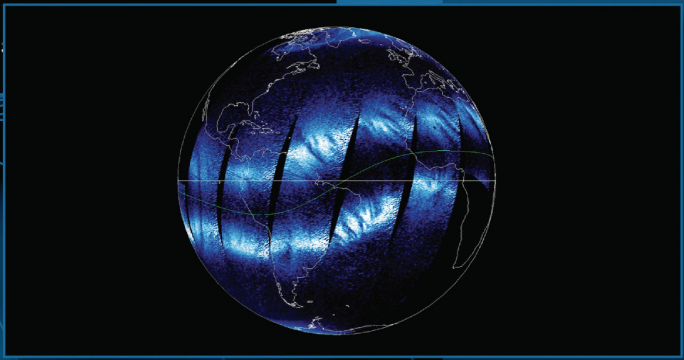
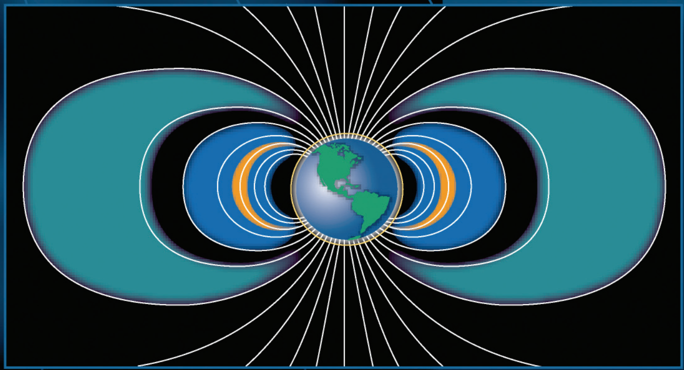
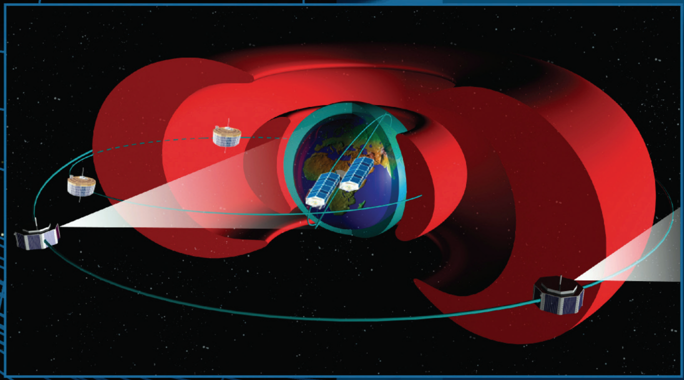
National Aeronautics and Space Administration

# Living With a Star Opportunities for Geospace Science

## A Strategy for the Geospace Missions







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# Living With a Star
# Opportunities for Geospace Science

A Strategy for the Geospace Missions

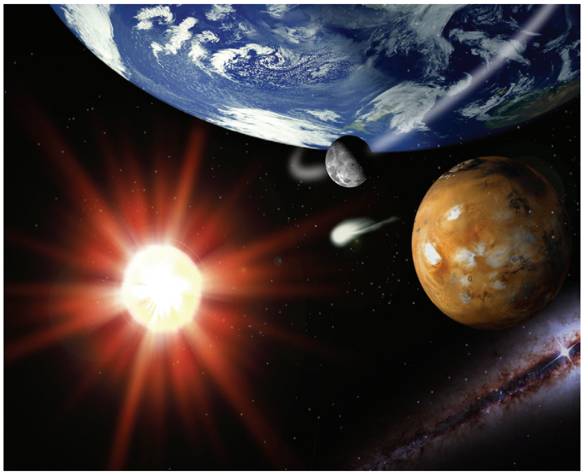
# Table of Contents

# 1. Geospace and the Solar-Planetary Environment: Visions of Exploration

*"The Fundamental Vision for U. S. Space Exploration is to Advance U.S. Scientific, Security, and Economic Interests Through a Robust Space Exploration Program."*

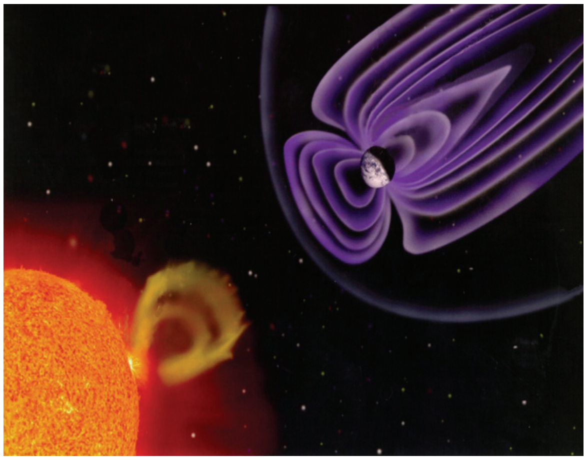
*(The Vision for Space Exploration, June 2004)*

The dawn of the space age opened exciting new opportunities for investigating the solar system and beyond. With bold visions of exploration NASA's scientific missions have led to radical revisions in our concepts of the solar system. No longer are planets viewed as isolated outposts within an empty wasteland called "outer space." We now recognize that not only atmospheres surround planets, but also magnetospheres and regions of electrically charged particles called ionospheres, and these themselves are immersed in a vast, continuous and dynamic medium – the solar-planetary environment.



The LWS program addresses the effects of the Sun's highly variable radiation and particle emission upon the Earth and other planets.

The Sun itself is much more than a simple, round white disk with dark sunspots. In addition to sunlight it emits radiation over a wide range of frequencies, from radio waves to X-rays and gamma rays. It also spews out an electrified gas, or plasma, composed primarily of positively charged protons and negatively charged electrons. With a speed of a million miles per hour, this plasma, called the **solar wind**, envelops and interacts with all the planets and other solar system bodies and dissipates far beyond the planets in its encounter with the interstellar medium, the environment between the stars. Bursts of electrically charged particles, accelerated to dangerous energies by electric and magnetic fields embedded in the solar wind, sporadically bombard these planetary environments.



The source of space weather, our dynamic Sun, shown with a coronal mass ejection that will interact with the terrestrial magneotsphere producing geospace storms.

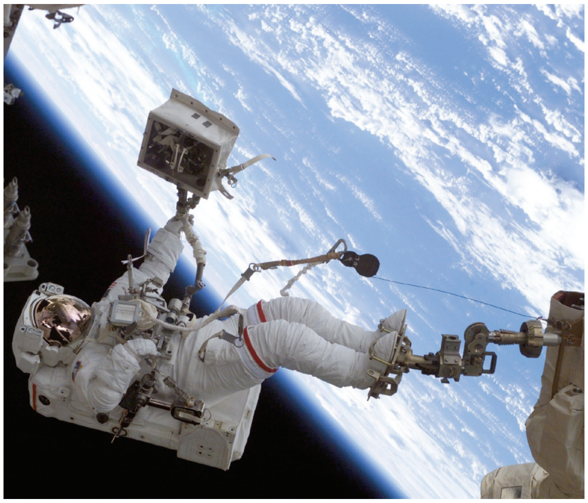
Atmospheres, ionospheres and magnetospheres shield the Earth and other planets from the bombarding solar particle emissions. These shielding regions – called **geospace** at Earth – harbor their own complex environments of electric fields, electromagnetic waves, and hazardous fluxes of energetic, electrically charged particles whose characteristics are controlled by energy extracted from the solar wind.

We call the solar wind driven variations in geospace, in its planetary counterparts and in interplanetary space "**Space Weather.**" Space weather defines the environment that exploration missions will encounter when voyaging to the Moon, Mars and beyond. Space weather effects, accumulated over a long period, can even impact the evolution of a planet's habitability.

With its bold vision of exploration renewed, NASA now plans to send beyond low Earth orbits robotic and human missions aimed at understanding the history of our solar system and searching for habitable environments. The designs for these missions must be optimized to accommodate the environments that are established and modified by space weather, which may include sensing and responding to impending hazards, modifying communication links that operate across the solar system, establishing appropriate hardening for infrastructure assets that operate in Earth orbit, and improving designs for capturing spacecraft into planetary orbits. Besides design considerations, operations must be warned of potentially dangerous variations in the mission environments as well as be assured of safe periods.

These designs and operational forecasting needs of the future can be met through strategic research that leads to an understanding of the complex web of interactions linking the Sun's emissions with the planets. Two kinds of research are required: one, **targeted research** to obtain the empirical information needed to characterize the relevant environments, and two, **basic research** to understand the fundamental physics of the solar/planetary system from which physics-based models will be developed to provide forecasting capabilities. This research is also key to further understanding the history of our solar system and unraveling the temporal history of planetary environments that lead to habitability.

Beyond NASA's own interests, our increasingly technological and space dependent society has economic and security needs that only NASA's solar system connections research can fulfill. As the vulnerability of our technologies become ever more obvious, the need to understand space weather and mitigate its effects becomes more urgent.



In Earth orbit and in interplanetary space humans are directly exposed to space weather and its potentially dangerous impact.

# 2. Geospace Within Living With a Star

*As Society Becomes Increasingly Dependent on Space-based Technologies, the Need To Understand Space Weather and Mitigate Its Effects Becomes More Urgent.*

A decade ago a number of government agencies (NOAA, DoD, DOT, DoI, DoE and NASA) and the NSF collaborated to draft a joint National Space Weather Program. Of these agencies, only NASA can provide the comprehensive end-to-end space-based observations needed to study and understand the complicated chain of phenomena leading from solar emissions to geospace responses. Recognizing the importance of space weather, NASA proposed a unique and comprehensive program called **Living With a Star (LWS) to provide the comprehensive observations and analysis tools needed to investigate those aspects of the Sun-planetary environment that directly affect life and society.**

The objectives of this program are to:

- Understand the sources of energy and electrically charged particles coming from the Sun that drive the changes in our geospace environment;

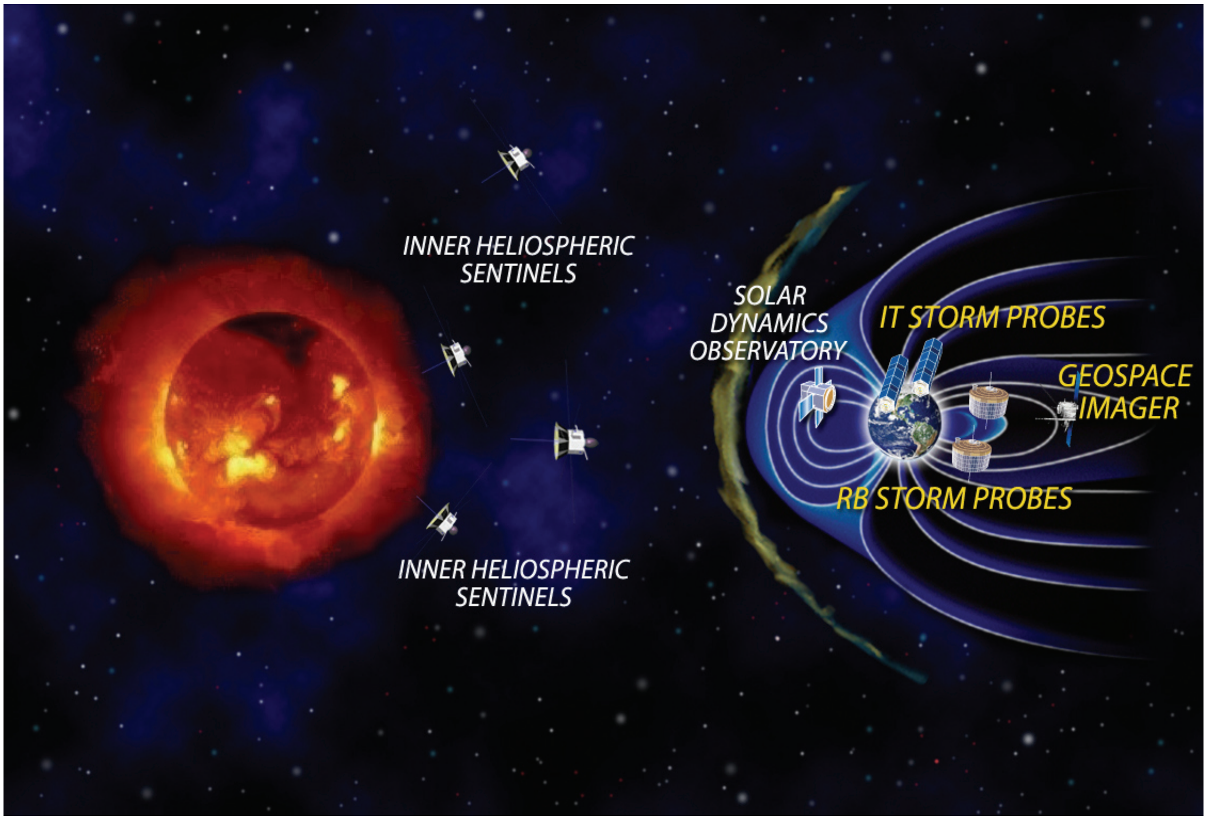
- Identify and understand the reactions of geospace to these energy and particle sources;

- Simulate and model the Sun-planetary system, from the sources of energy and particles on the Sun through the reactions of geospace, to enable forecasting of the geospace environment;

- Extend our knowledge and understanding gained in this program to explore extreme solar- terrestrial environments and implications for life and habitability beyond Earth.

The approach selected to accomplish these objectives is unique among the NASA science programs. LWS is to have dual tasks: one studying solar-terrestrial physics to understand basic natural processes, and the other developing investigations into phenomena that specifically have societal consequences. It is particularly noteworthy that the fourth objective was enunciated by NASA's advisory committees and adopted by the LWS program in 2001, well before the President's Exploration Initiative, testifying to the key role that exploration plays in the LWS program.

The LWS program will provide the comprehensive observations needed to unravel the interrelationships between the sources and reactions of the Solar-geospace system by an array of spacecraft in both interplanetary and geospace (Figure 2.1). The **Solar Dynamics Observatory** will use helioseismology (the solar counterpart of seismology at Earth) to detect changes within the Sun that lead to variations in its emissions, even on the back side, image the Sun at multiple wavelengths to link these changes to those occurring at the Sun's surface, and monitor the extreme ultraviolet irradiance that exerts a controlling influence on the variability of planetary ionospheres. The **Geospace Storm Probes** will investigate the highest priority and most strategic responses of the Earth's magnetosphere, ionosphere and upper atmosphere (the thermosphere) to the varying solar plasma and electromagnetic emissions. The **Heliospheric Sentinels**, located midway between the Sun and the Earth, will track the huge transient emissions of matter from the Sun, called coronal mass ejections (CMEs), that drive geomagnetic storms, and detect dangerous solar energetic particle events.




The LWS program will provide the comprehensive array of spacecraft and instruments needed to construct track and understand space weather effects throughout the heliosphere. Once this understanding has been obtained, we will be able to construct the predictive models to ensure successful mission operations.

The LWS program will need to work with other national and international spacecraft and ground-based assets. For example, the Solar Probe will plunge into the vicinity of the Sun to make critical observations of the origin of the solar wind. The two STEREO spacecraft will provide in-situ measurements of solar wind phenomena many hours before they reach Earth and obtain stereo images of CMEs from vantage points far off the Sun-Earth line to determine unambiguously their direction, speed and size. The joint DoD/ NASA C/NOFS program will provide observations of low-latitude ionospheric irregularities. Ground-based facilities will measure aspects of the Earth's ionosphere/thermosphere system complementary to the Geospace Storm Probes.

Interpreting the geospace observations and putting them to practical use requires comparison with theory and the development of a host of models. The Targeted Research and Technology (TR&T) component of the LWS program focuses on analyses and model development of the greatest relevance to the LWS program in areas where progress is most likely to provide practical results. Results from the TR&T program will be transitioned to industrial and governmental partners.

# 3. The Role of Geospace

*It is in Geospace Where Human Technologies Encounter Phenomena Driven by Solar Activity*

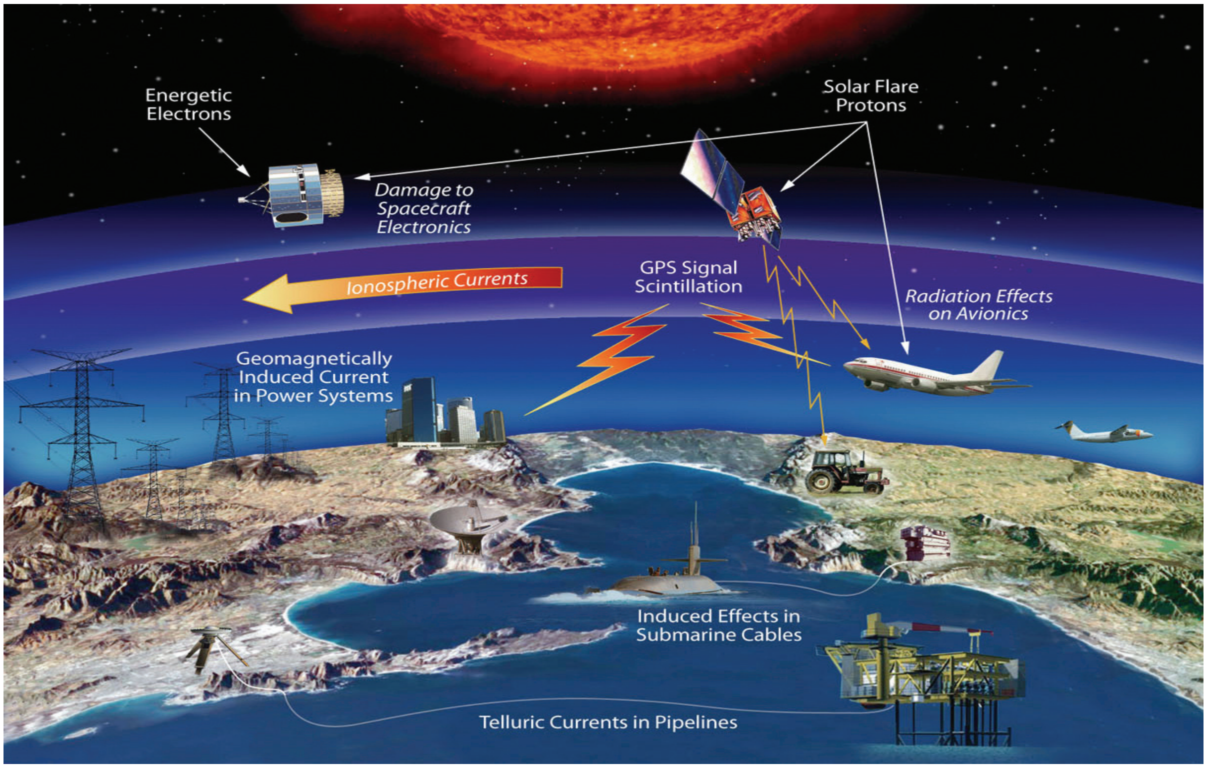
The upper region of the space that surrounds the Earth – geospace - is populated not only by the neutral atmosphere but also by ionized gases. These gases include the ionosphere at low altitudes and energetically charged particles trapped in the Earth's magnetic field at higher altitudes. Different solar emissions drive the dynamics and energetics of these populations. Like the familiar weather on Earth, space weather within planetary geospaces can be mild, moderate, or severe. And like the severe weather at the surface of the Earth the severe weather in Earth's geospace can adversely affect human-initiated activities. Indeed, **it is in geospace where human technologies encounter phenomena driven by solar activity.** Similar interactions will affect technological systems in the analogous environments of other solar system bodies.

At Earth, two regions of geospace are particularly relevant to human activities: the radiation belts and the ionosphere/thermosphere.

The dynamics of the Earth's radiation belts have received renewed attention in recent years due to the discovery of an intense but transient belt and to society's increasing reliance on space systems that must operate in the harsh environment of high-energy charged particles. During **magnetic storms**, the most significant geospace weather activity, some of the already energetic trapped particles in the radiation belts are accelerated to near relativistic energies. How this acceleration occurs remains an open and pressing question, precluding the prediction of storms.

Recent global measurements have revealed that the magnetosphere and ionosphere interact much more strongly than previously appreciated. During geomagnetic storms solar wind energy transmitted through the magnetosphere greatly perturbs the Earth's ionosphere and upper atmosphere, producing strong density gradients that spawn irregularities and scintillations. Powerful storm-time electric currents course through the Earth's ionosphere, heating and expanding the upper atmosphere at high-latitudes; while energetic particles accelerated within the magnetosphere precipitate into the atmosphere to generate aurora. Both effects modify the thermospheric densities and winds and greatly increase ionospheric densities, and thus conductivities for electric currents, especially on the night side. A global approach is required to understand the ionospheric and thermospheric structures generated by local and remote energy sources. This is particularly true for features that occur at the mid- and low-latitudes where most people live.

Besides posing a hazard to human health, the radiation in the radiation belts is responsible for spacecraft charging and discharging, single event upsets to computer electronics, and material degradation. The ionosphere/thermosphere disturbances interfere with the functioning of important military and commercial communications and navigation technologies, cause range errors of tens of meters in the Global Positioning system (GPS), disrupt high-frequency radio communications and military radar systems and reduce the lifetimes of low-altitude orbiting spacecraft. While the processes that cause these practical consequences occur in varying manifestations at other planets and bodies throughout the solar system, it is only at Earth where they can be sufficiently probed and measured in detail to understand the physics.




The impacts of space weather range from deleterious effects in space to effects on technology systems on the Earth's surface.

In keeping with the unique LWS dual approach of studying basic natural processes that specifically have societal consequences, the LWS Geospace Program has identified and prioritized its most strategic objectives (see Appendix A). Two have highest priority with the potential for significant progress (see table below).

Because it is in geospace that the physics controlled by solar emissions interacts with the technologies of humans, the implementation of the LWS Geospace program's strategic objectives will advance U.S. scientific, security and economic interests as envisioned by the **Vision for Exploration.**

| LWS / GEOSPACE HIGHEST PRIORITY STRATEGIC OBJECTIVES |
| --- |
| **Radiation Belt Strategic Objective:**<br>*Characterize and understand the acceleration, global distribution and variability of the radiation belt electrons and ions that produce the harsh environment for spacecraft and humans.* |
| **Ionosphere/Thermosphere Strategic Objective:**<br>*Characterize and understand ionospheric variability and its irregularities that affect communications, navigation and radar systems.* |

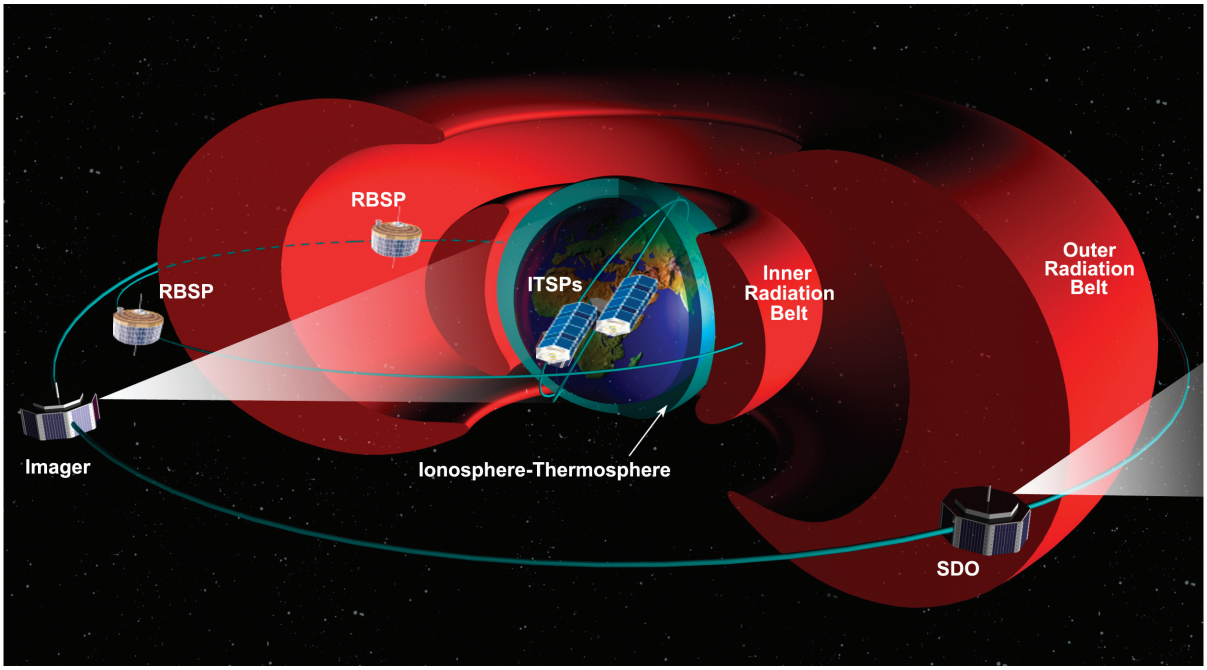
# 4. Implementing the Geospace Program

*The LWS Geospace Program has been Carefully Crafted to Target its Highest Priority Strategic Program Objectives.*

The LWS Geospace Program has been planned as a program of “targeted” basic research that includes flight, collaborative and theory components. The important flight elements of the Geospace Program are:

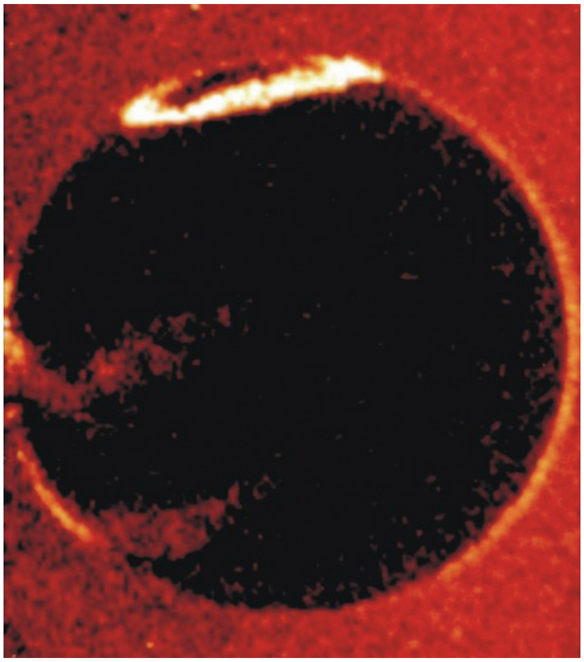
• **Two Radiation Belt Storm Probes (RBSP)** in highly elliptical, low inclination orbits with instruments targeting the particles and fields of the harsh electron radiation belt environment that are responsible for the major geospace weather activity during magnetic storms. They will be identically equipped with detectors to measure the relativistic electrons, ring current ions, the geospace electric field, magnetic field perturbations and the electromagnetic waves that fill geospace. This will be the first multi-spacecraft science mission into the inner magnetosphere giving the dual point measurements needed to decipher the various candidate particle energization mechanisms.

• **Two Ionosphere-Thermosphere Storm Probes (ITSP)** in low altitude, 60° inclination orbits separated in longitude about 15° with instrumentation targeted to observe the dynamics of the ionospheric plasma and residual neutral atmosphere in the region where they are particularly coupled. They will be equipped with identical thermal plasma, neutral particle and wind, irregularity and electric field detectors. Similarly, ITSP will be the first dual satellite mission into the ionosphere-thermosphere system with the capability of measuring the gradients of the plasma parameters in two dimensions that are essential for understanding the physical processes that drive the structures of the system.•




The components of the Geospace missions are shown in relation to the radiation belts (red) and ionosphere-thermosphere (IT) system (blue). They consist of 2 satellites in the radiation belts, two in the IT, a remote sensing imager and an EUV instrument on the SDO Spacecraft.

• An **Ionosphere-Thermosphere Imager** for global measurements of the ultraviolet light emissions from the upper atmosphere (called airglow) in the ionosphere-thermosphere system. The imager's observations will define the global response of the IT system to changes in the energy input from the solar EUV emissions and from the magnetosphere during magnetic storms. They will also place into a global context the in-situ measurements from the ITSP spacecraft and collaborating missions and ground-based facilities. This imager will be flown on a mission of opportunity having an apogee sufficiently high to allow global observations.



Space-based ultraviolet measurements can reveal variations in auroral activity (bright ring at top), an indicator of magnetosphere energy inputs, and equatorial ionosphere structures (the two bright arcs on the lower left bound the equator).

Observations or models for the extreme ultraviolet solar radiation are crucial to understand the ionosphere-thermosphere system, since they provide a measure of the dominant energy input into the system and allow the ground state to be determined upon which the magnetospheric energy inputs are superposed. Observations by the EVE instrument on SDO, or models based upon these observations, will satisfy this need.

Since the IT Storm Probes mission targets the mid-latitude storm-time phenomena, a global analysis of the ionosphere-thermosphere response to variable solar and magnetospheric energy input will require significant collaborations. Early in the program, observations of the irregularities in the low-latitude ionosphere will come from the joint DoD/NASA C/NOFS mission. During the ITSP flight epoch, multiple sources of auroral and high latitude data will provide the highly variable energy input measurements to the ionosphere and thermosphere in these regions, where they are especially important on the nightside.

An integral element of the LWS Geospace program is the development of models that will incorporate improved understanding of the physics of these two regions, leading to realistic real-time specifications of the space environment (nowcasting) and accurate predictions of potentially hazardous space weather conditions (forecasting).

The LWS Geospace program has been well crafted to include the three required components of flight missions, collaborations, and theory.

# 5. Earth's Radiation Belts and Particle Acceleration

*The Most Important Attribute of the RBSP Mission Must be the Multiple, Simultaneous Measurements of the Radiation Belt Needed to Distinguish Between Particle Acceleration Mechanisms.*

From the very onset of the space faring era, scientists noted a strong relationship between variations in the intensity of the radiation belts and enhanced geomagnetic activity. Over the years they have proposed a plethora of source and loss mechanisms to account for these fluctuations. The source mechanisms typically invoke inward transport and particle energization from an existing low energy population, while loss mechanisms include precipitation into the atmosphere or escape through the magnetopause. We think now that the generation of the extremely energetic ions and electrons of the belts during magnetic storms involves a number of fundamental processes acting in concert over multiple temporal and spatial scale sizes.

Global scale processes involve transport of charged particles from the weak magnetic field of the distant magnetosphere to the strong field of the inner magnetosphere. Energization occurs because the ratio of energy to magnetic field is conserved. These transport processes include:

1) *Global-scale electric fields;*

2) *Radial diffusion* by fluctuating global-scale electric and magnetic fields;

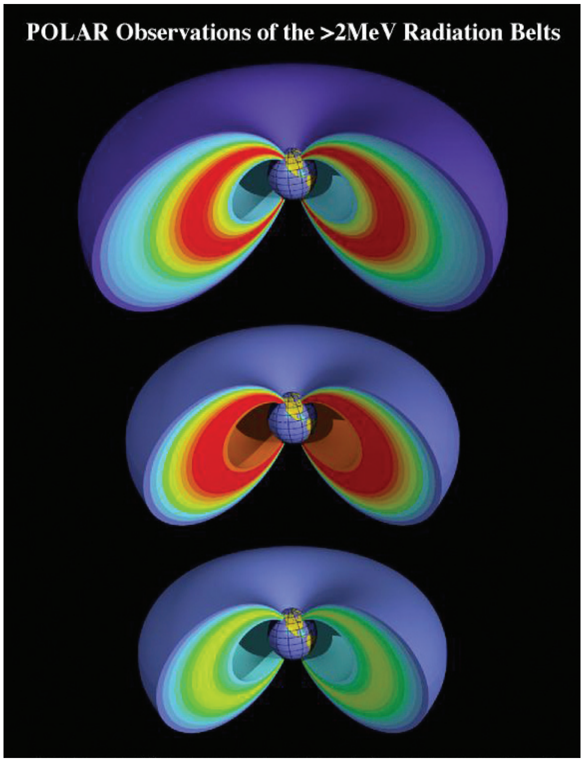
3) Large-scale *electromagnetic ultra-low-frequency (ULF) waves;*

4) *Prompt acceleration* by interplanetary solar wind *shocks* that hit the magnetosphere and induce intense compressional wave fronts that surge through the inner magnetosphere;

Local processes involve:

1) Rapid *local acceleration* of particles by the huge *inductive electric fields* produced by rapidly changing magnetic fields associated with geomagnetic storms;

2) The *exchange of substantial energy* between electromagnetic *ion cyclotron (EMIC) waves and Very Low Frequency (VLF) chorus waves* generated in the inner magnetosphere and charged particles trapped along the magnetic field lines.



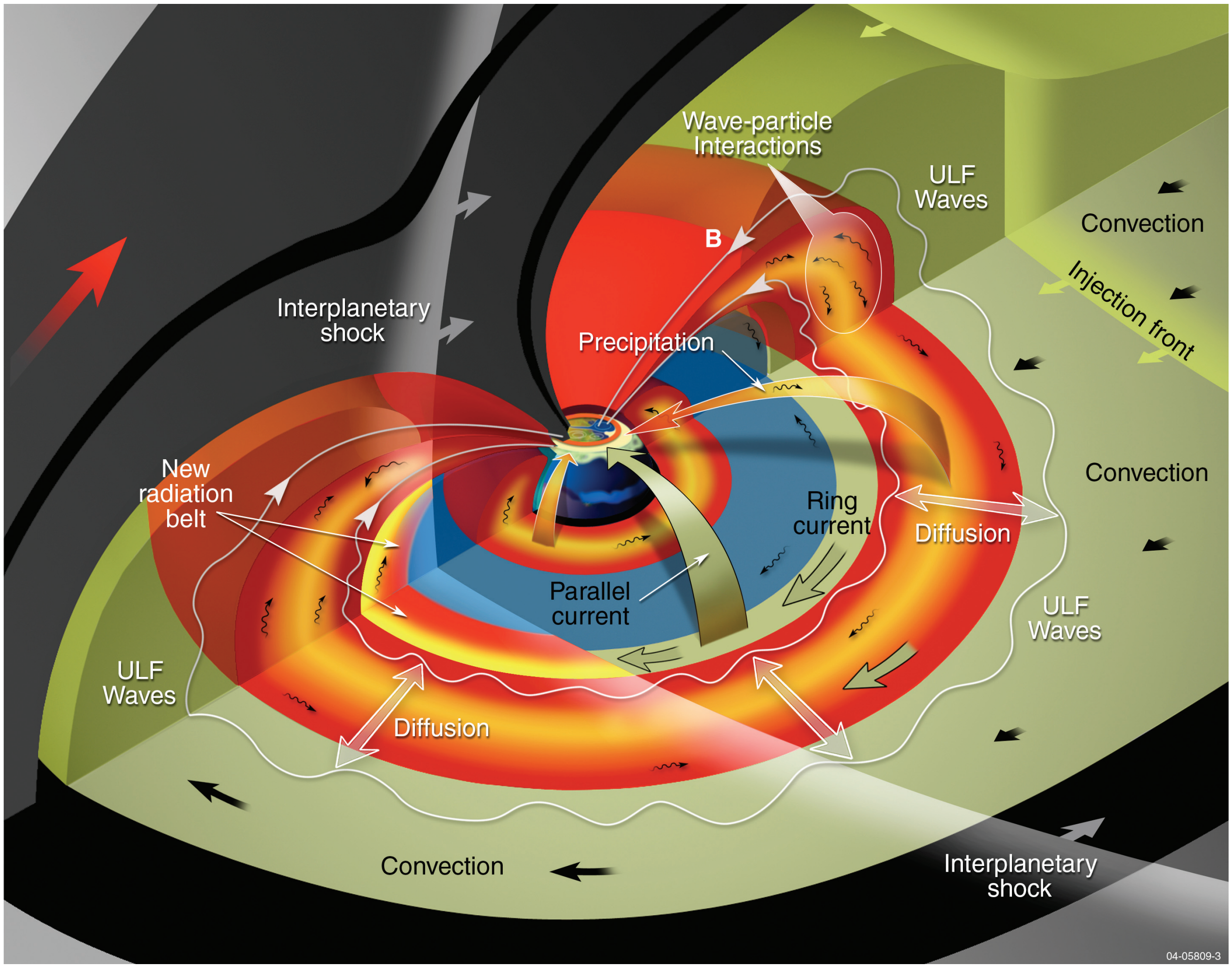

On subsequent 18-hour measurements of the radiation belts, changes in both size and intensity of the belts occurred. (Red is one million times more intense than blue). The prediction and mitigation of radiation effects on human flight and spacecraft systems will only be possible when causes of radiation belt changes are understood. *Image: G. Reeves (Los Alamos National Laboratory)*

Each of these processes should leave a specific temporal and spatial signature in the distributions of the energized particles. Each can be understood in a fairly straight-forward manner when viewed as an isolated energization mechanism. However, when all of these processes respond to the transient energy input from the solar wind during geomagnetic activity by varying degrees, our understanding of which mechanisms dominate is severely challenged. This challenge can be overcome with a new kind of mission, the Radiation Belt Storm Probes (RBSP).

A single spacecraft, however well instrumented, cannot provide the observations needed to distinguish between the various transport mechanisms and from local acceleration mechanisms. As a consequence, the most important attribute of a radiation belt mission must be multiple, simultaneous measurements of the radiation belt region. The mission must utilize a minimum of two spacecraft to obtain the temporal variations of the radial distributions of the charged particles and fields. One spacecraft should reside in the region that particles are transported from while the other resides in the region that the particles are transported to.

To accomplish this, two identical spacecraft must be placed into a common near-equatorial elliptical orbit (apogee of ~5.5 Earth radii) where they will slowly separate in phase around the orbit. As the separation evolves the measurements of the temporal, radial and azimuthal distributions of the charged particles and the electric and magnetic fields will enable the selection of the dominant mechanisms and thus the physics operating under particular conditions.

This increase in the understanding of the physics will allow the development and validation of sophisticated physics-based simulation models of the radiation belts that represents a vital step towards understanding and predicting the generation of penetrating radiation throughout the solar system.




The chain of processes coupling the inner magnetosphere energetic particle environment to solar wind disturbances is shown.

# 6. The Ionosphere-Thermosphere (IT) System

*The ITSP Missions Will Provide the Observations Needed to Understand the Ionospheric and Upper Atmospheric Structures that Most Affect Technological Systems.*

The ionosphere has been studied since the discovery of its effects on radio communication over a century ago. However we have only recently begun to identify the dramatic impact of its variability on advanced technological systems, particularly those functioning at the low- and middle-latitudes where most people live. A firm understanding of ionosphere-thermosphere (IT) variability is needed to reliably operate these systems at Earth and to develop similar capabilities for the exploration of Mars and other solar system bodies. The multispacecraft and multi-instrument ITSP missions will provide the comprehensive in situ and remote observations needed to attain this understanding.

Two energy inputs govern the fundamental processes occurring in the IT regions. Solar Extreme Ultraviolet (EUV) radiation photoionizes the neutral thermosphere to create virtually the entire dayside ionosphere, and the associated heating introduces thermospheric pressure gradients that drive winds from the dayside into the nightside. The other energy source is the solar wind, whose energy is mainly deposited in the high latitude ionosphere by energetic charged particle precipitation and by electric fields that directly drive ionosphere motion and frictionally heat the lower thermosphere. This heating drives thermal gas upwellings that change the composition of the upper thermosphere and initiate equatorward-propagating atmospheric gravity waves, horizontal thermospheric winds, and additional composition changes. The global ionospheric morphology depends on atmospheric chemistry, collisions with neutral winds, and the complicated sequence of energy inputs from geomagnetic storms. These processes generate considerable IT variations over a range of spatial scales, which can develop into steep local density gradients that become unstable, generating small spatial scale irregularities. While we understand how some IT phenomena operate in isolation, we do not understand how they interact in the midst of complex and time-varying energy inputs to produce these global variations and local gradients. Furthermore, we have almost no ability to predict the resulting irregularity distributions. The latter prediction is crucial since the irregularities randomly perturb radio waves propagating through the ionosphere, resulting in scintillations that can disrupt communications and GPS operations.

The impact of solar wind energy on Geospace is particularly evident during geomagnetic storms, when magnetospheric energy inputs increase rapidly and the most prominent IT structures develop and propagate. The ionosphere responds with two distinct storm phases. In the initial, positive, storm phase, enhanced IT motions and composition changes promptly generate mid-latitude ionospheric density enhancements. *These density enhancements can be extremely large and longitudinally confined, with irregularities developing on their sharp boundaries. In the absence of comprehensive measurements, we don't understand why these features occur or how they develop.* During the second, negative, storm phase, coupling of the ionosphere with persistent neutral atmosphere storm-induced perturbations and other effects generate mid latitude ionospheric density depletions. This latter phase endures long after the geomagnetic storm ends and results in ionospheric structures that also affect technological systems. *The evolution of the neutral winds and electrodynamics underlying these features remains very poorly characterized, making it nearly impossible to* *predict the development of sharp ionospheric spatial gradients and irregularities.*

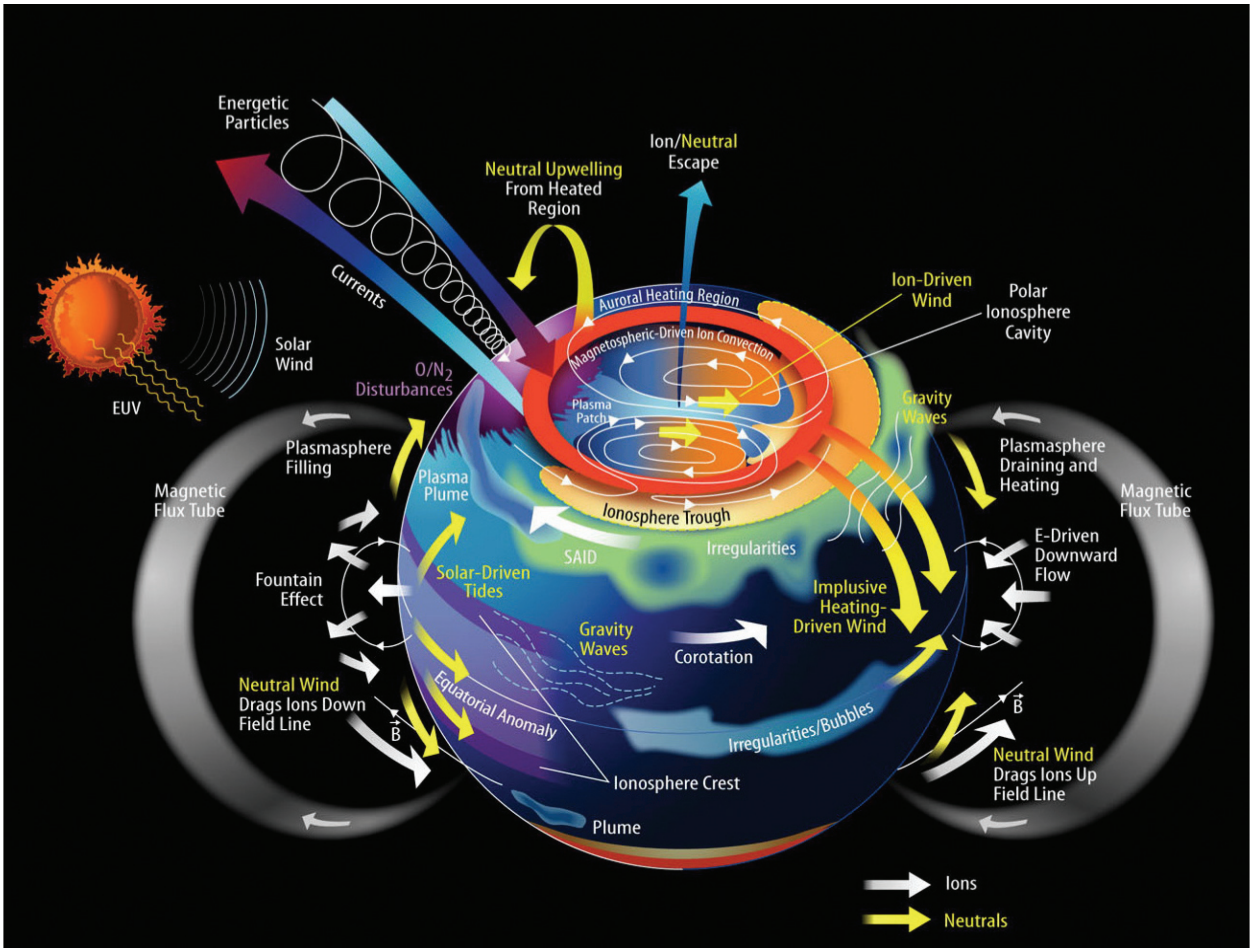
The gaps in our understanding of the responses of the ionosphere/thermosphere system to magnetospheric energy inputs, and our need for a predictive capability, can only be filled with comprehensive quantitative measurements of the energy inputs and ionospheric/thermospheric responses in situ and on a global scale. Two identically-instrumented IT Storm Probes (ITSP's) will make line cuts through the ionosphere and thermosphere to provide the observations needed to understand the evolution of mid-latitude storm structures and identify when and where radio scintillations develop. These in situ measurements must be made at altitudes ranging from 450 to 500 km, where the neutral density suffices to allow measurement of the important neutral winds and atmospheric drag effects do not seriously impact the spacecraft lifetime. Moderate orbital inclinations of ~60° enable the spacecraft to measure mid-latitude longitudinal variations and cut through the northern and southern dayside and nightside hemispheres with revisit times that suffice to track the evolution of ionospheric storms. Maintaining a longitudinal-separation of ~15° between the spacecraft pair permits determination of the azimuthal extent of midlatitude storm structures. High-resolution in situ measurements of the relevant neutral gas and ionized plasma parameters will reveal the local physics governing the development of radio scintillations. An IT imager on a mission of opportunity will provide the global context and more rapid revisit times for these in situ measurements by mapping nightside electron density structures and dayside thermosphere compositions.

Other missions will supply crucial information concerning the solar and magnetospheric energy input into the ionosphere-thermosphere system. While the ITSP will occasionally encounter the high latitude regions where magnetospheric energy enters the IT system, observations of this input will be more routinely obtained from other spacecraft (e.g., NOAA's NPOESS) and ground facilities (e.g., the SuperDARN radars). Because geomagnetic storms rearrange the baseline mid-latitude IT state created by solar EUV, information concerning EUV irradiance before, during, and after geomagnetic storms is also essential. This information will be obtained from the simultaneous high resolution Solar Dynamics Observatory (SDO) EUV observations, and/or from solar EUV flux models derived on the basis of observations made by past (SNOE), present (TIMED), or future (SDO) NASA missions. Finally, data from a wide range of sources, including ground-based/spaceborne GPS measurements of the ionospheric electron density, radio sounder profiles of the ionospheric structure, and mid-latitude radar observations of ionospheric motion will assist in interpreting the ITSP observations.

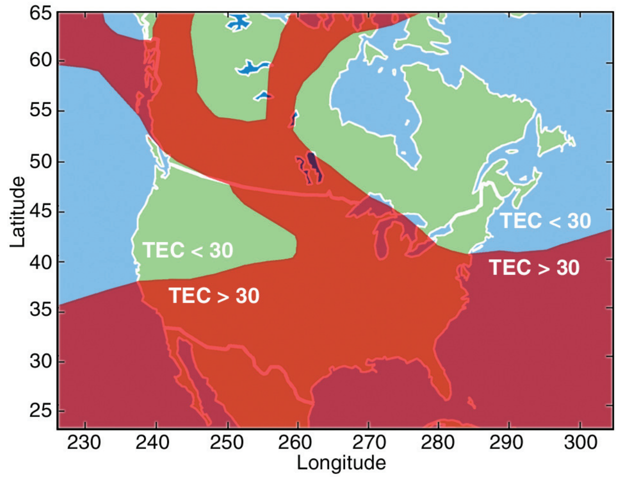
Enhanced understanding and quantification of the terrestrial IT variability will help validate physics concepts and current physics-based models. ITSP data will be assimilated into these models to help specify and predict the space weather conditions faced by technological systems at Earth. Since the physical processes operating at Earth are equally applicable to other planetary atmospheres, most planetary atmosphere models (e.g., the various Mars atmospheric circulation models) are based on terrestrial counterparts. By validating models for Earth, the ITSP program will help in the development of next-generation planetary atmosphere models for future exploration needs.

## IT Science Objectives

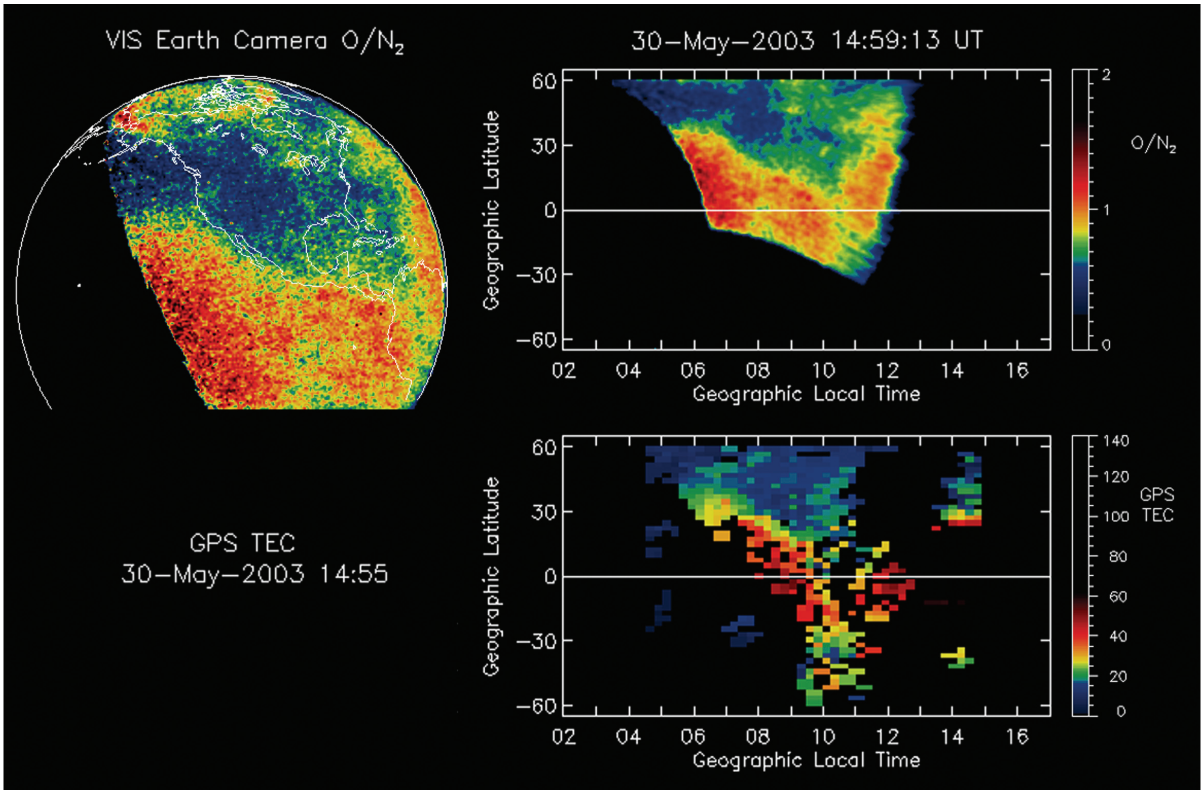
1. How does the low- and mid-latitude IT system respond to geomagnetic storms and changing solar EUV?
2. What are sources and characteristics of irregularities at mid-latitudes?
3. What are space weather effects of ionosphere variability at mid-latitudes?




The prominent features in the ionosphere-thermosphere system and their coupling to the different energy inputs show the complex temporal and spatial phenomena that are generated.




The vertical electron content from groundbased measurements of GPS signals have revealed complex temporal and spatial variations over U.S. longitudes.




Remote ultraviolet images of structures in the thermospheric oxygen distribution (left) and the ratio of O/N2 (top right) are shown during a geomagnetic storm. Troughs (blue regions) in the oxygen concentration and in the O/N2 ratio form and change with time in association with storm activity. The ionosphere total electron content (bottom right) during this period also showed the development of enhanced bands stretching to middle latitudes attributed to electric fields. To resolve these structures and their causes, multiple satellite in situ observations of the IT variables as well as global scale imaging are needed.

# 7. Closure Through Theory and Modeling

*Theory Will Provide the Interpretation of the Geospace Data and Modeling the Tools to Enable Space Weather Forecasting.*

In addition to expanding the frontiers of science, the success of the LWS Geospace program must ultimately be borne out by substantial improvements in space weather services. While theory provides the framework to interpret the observations returned by the Geospace missions, models provide the means to codify, validate, and transition discoveries to operations. The Geospace program will therefore work hand-in-hand with developers of tools and models, especially those sponsored by the Targeted Research and Technology (TR&T) component of the LWS Program.

The ultimate goal of the LWS program is to provide an end-to-end data assimilation first-principles model linking the prediction of solar energy and particle emissions to expected interplanetary and planetary space weather phenomena. A comprehensive model of this type does not presently exist, but the research community is poised to initiate one from the wide range of currently available empirical, nowcast, and forecast models that describe conditions in different regions of space. However, the algorithms for most of these models are not based on first principle physics, so they don't capture the consequences of the real underlying physics. It is therefore the responsibility of the LWS Geospace program to identify the key processes that must be included within the Geospace modules of the end-to-end model and to provide the observations needed to test these modules. Until such time as a comprehensive end-to-end model becomes available, the operational community will continue to rely upon its panoply of purpose-built region-specific models.

For design and mission planning purposes the user community also needs various climatological and empirical models, based on long-term statistical information, that are aimed more at characterizing the environment than on understanding it. For this purpose data are needed over a wide range of geophysical conditions, with emphasis on the extremes.

Specifically, the theory, modeling and operations communities require from the Geospace Investigations the following types of data:

• Highly resolved measurements of energetic electrons and ions through the heart of the radiation belts, and the electric and magnetic field properties of the magnetosphere, especially during magnetically active periods. These data will enable:

- the development of modern empirical models of the radiation belt environment for satellite design work;

- the development of radiation belt models based on an understanding of the physics of particle acceleration and loss, for prediction capabilities;

- after-the-fact satellite problem analysis.

• Solar EUV measurements of the variable solar energy input to the atmosphere enable:

- the determination and modeling of the ground state of the ionosphere-thermosphere system for the first time,

- construction of a baseline for the large perturbations of the system during magnetic storms.

• In-situ measurements of the ionospheric plasmas, thermospheric neutral properties and global measurements of electron densities in the ionosphere-thermosphere system, especially during geomagnetic storms, to enable:

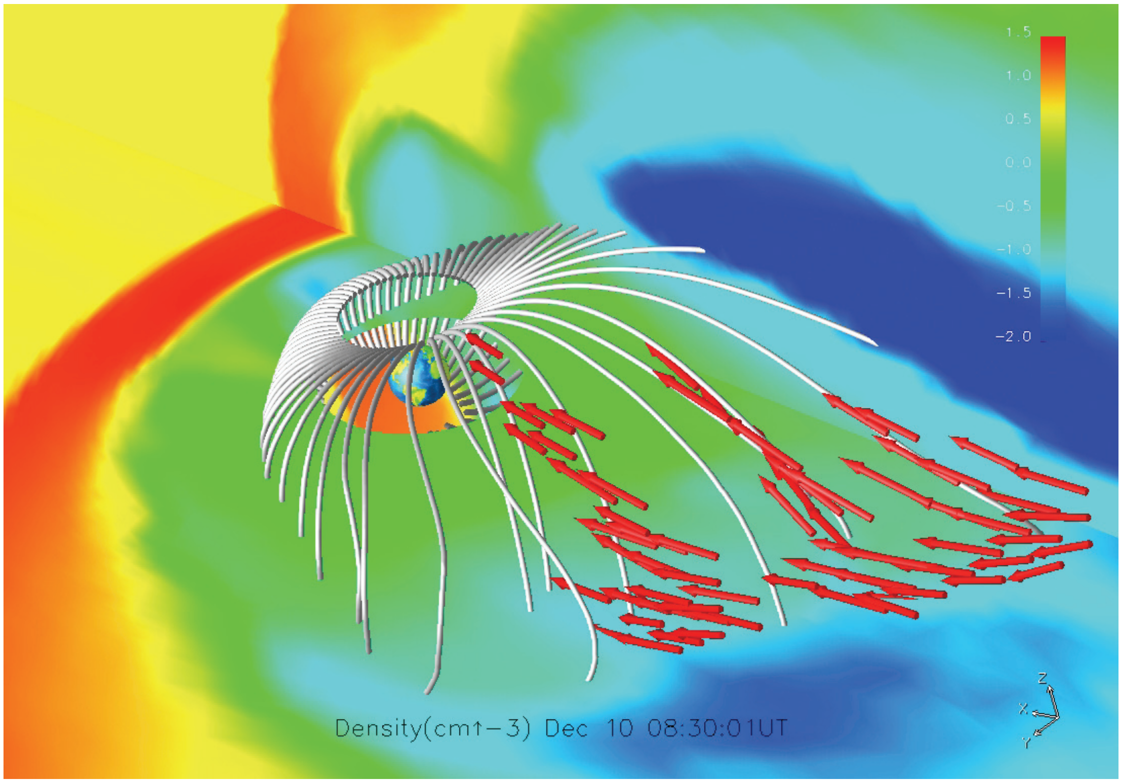
- the development of high resolution first principles models of the coupled magnetosphere-ionosphere-thermosphere system to understand and eventually predict ionospheric gradients and irregularities responsible for scintillations that affect communication and navigation systems.

- the development of vastly improved climatological models of the ionosphere and thermosphere especially for satellite drag determinations,

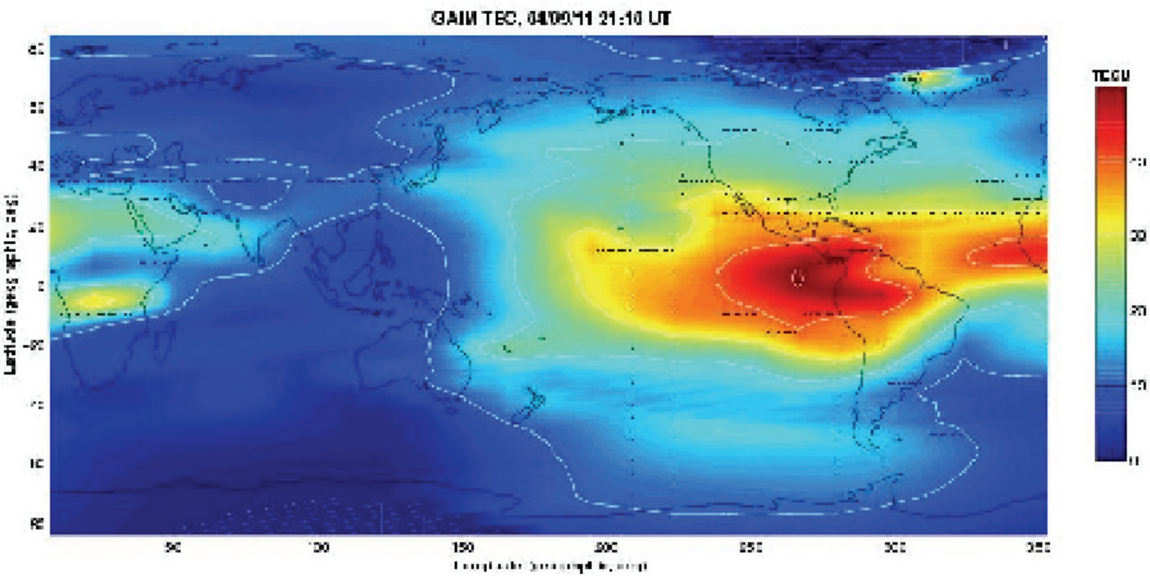
• Combined radiation belt, electrodynamic and ionospheric/thermospheric parameters to enable:

- testing of large fully-coupled solar wind/magnetosphere/ionosphere/thermosphere physics based models that will be the foundation of future nowcast and forecast operational models.

Timely acquisition of the data from the ITSP mission with SDO EUV monitoring data and the RBSP mission are critical for model-development work. Besides the LWS supported TR&T modeling effort, NASA's Community Coordinated Modeling Center (CCMC), the DoD-sponsored Multi-University Initiatives (MURIs) and the NSF Science and Technology Center for Space Weather Modeling (CISM) will be key collaborators.



Numerical simulations define the response of the magnetosphere to varying solar wind conditions. Plasma densities are color-coded (red = high, blue = low). Red arrows indicate plasma flows, and the white curves define the magnetic field lines bounding the Earth's magnetosphere. *Figure: C. Goodrich*




A global snapshot of the total electron content from the GAIM model. GAIM is a global, fully three-dimensional, and time-dependent ionospheric model. It numerically solves for ion and electron volume densities through the hydrodynamic equations for individual ions. The model is based on the first-principles ionospheric physics and incorporates state-of-the-art optimization techniques that provide a powerful capability of assimilating various types of ionospheric measurements. GAIM's data assimilation capability enhances the modeling accuracy significantly and helps to specify the Earth's ionosphere realistically. GAIM currently employs line-of-sight total electron content (TEC) measurements made from ground-based GPS receiver networks and space-borne GPS receivers, satellite UV limb scans, and ionosonde. Intensive validation has also been conducted using various independent data sources, including vertical TEC measured using satellite ocean altimeter radar (such as those aboard TOPEX and Jason-1 missions), ionosondes, and incoherent scatter radar.

# 8. Connections To Technology and Society

*The LWS Geospace Program is the Only NASA Program Whose Goal is to Mitigate the Vulnerability of Important Elements of Our Technological Infrastructure Located in Geospace to Space Weather.*

The number of satellites operating in Earth's harsh space environment and the variety of functions these satellites perform to support human activities have grown explosively since the dawn of the space age in 1957. Humans now depend on satellites for purposes that range from commercial enterprises to military functions, especially in the area of communications, as well as platforms for scientific exploration of the Earth, its environment, and the Moon, Mars and beyond.

The LWS Geospace program has targeted its missions to the most strategic regions of geospace that interact with the space-based and Earth-based technologies of humans. Within these regions, a variety of interactions occur:

*Energetic charged particle* components in the Earth's radiation belts produce differential surface charging on satellites that under geomagnetic storm conditions is strong enough to result in electrical discharges into the satellite power system. *Relativistic electrons,* such as those that exist in the outer "Van Allen" radiation belt, can induce deep dielectric or bulk charging of spacecraft coaxial cables and circuit boards, again producing discharges that damage electronics or modify memories. *High-energy ions* induce single event upsets that cause device tripping, component latchups, and bit flips in memory storage devices. Further the *accumulated dosage* of energetic particles can produce material degradation, especially on exposed surfaces. Hence the consequences can range from simple upsets in satellite electronics, from which recovery is relatively easy, to total mission failure.

The *low energy charged particles* comprising the ionosphere are also important. During a geomagnetic storm, the ionosphere complexity increases - the vertical electron content is considerably altered, density gradients intensify and large amplitude, small spatial-scale irregularities develop. These perturbations have significant impacts on the reliability of radio wave systems, such as GPS navigation and satellite communication, and on over-the-horizon radars, trans-ionospheric radars and secure high-frequency (HF) communications. While the ionosphere complexities have been most noted in auroral region structures and in the development of equatorial "Spread-F" irregularities, recent observations have shown surprising variations in what was thought to be a benign mid-latitude region. As man explores other planets similar ionospheric perturbations will need to be considered in the planning of communication systems.

Even the high altitude neutral atmosphere, the *thermosphere*, plays an important role due to its expansion during magnetic storms, yielding increased densities at altitudes of low Earth orbiting spacecraft that change their orbits and decrease their lifetimes.

The goal of the LWS Geospace program is to attain the understanding of the physics of these regions needed for the development of sophisticated new models of the geospace environment and the data bases for the development of specification and empirical models of the regions. These models will:

• Specify the nominal and extreme cases of the space environment;

• Provide assessments of those environments during specific periods of interest (nowcasting), and ultimately;

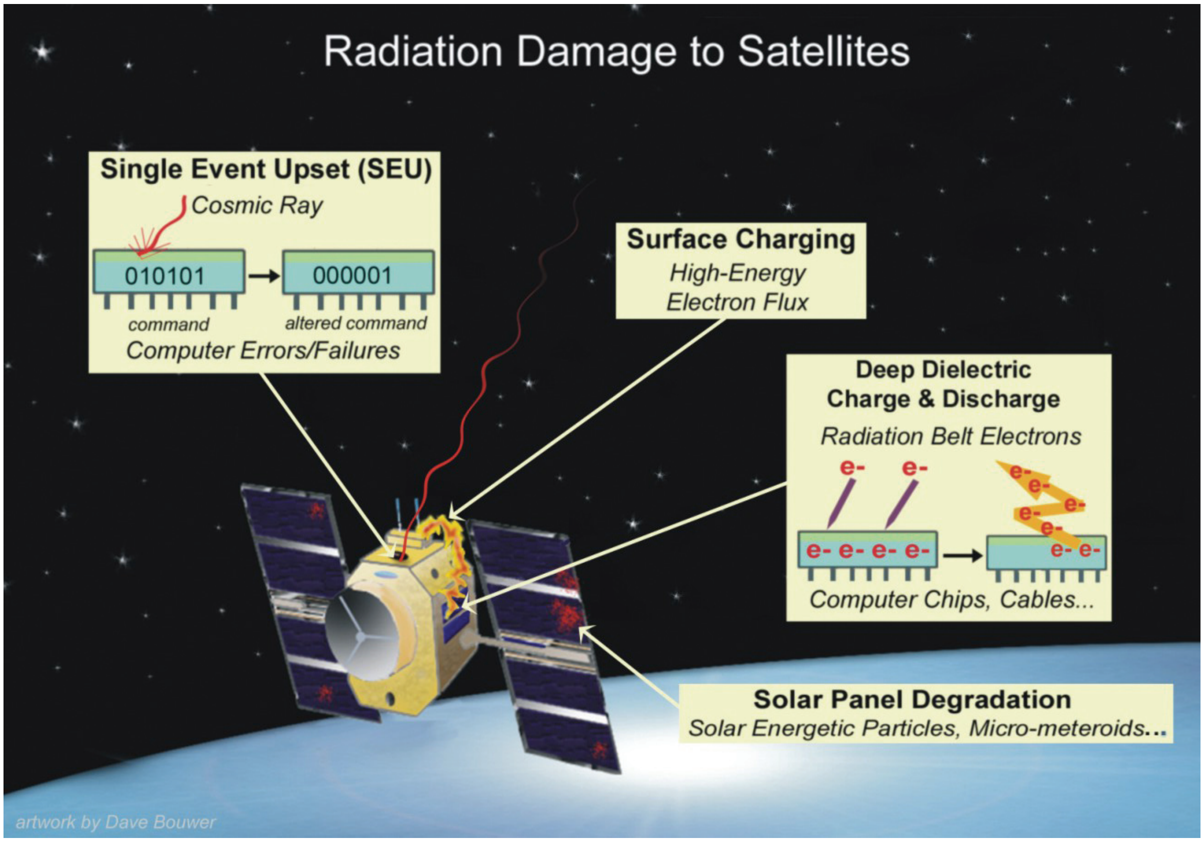
• Predict future environments (forecasting).

**Specification or empirical models** are of great value both to the developers of technology and to users of new technologies that are being developed. This user community includes, for example, designers and manufacturers of spacecraft, communications systems, and navigation systems. Also included are those responsible individuals and agencies that must decide which technologies to implement. An example is the use of Global Positioning System (GPS) receivers in air transportation.

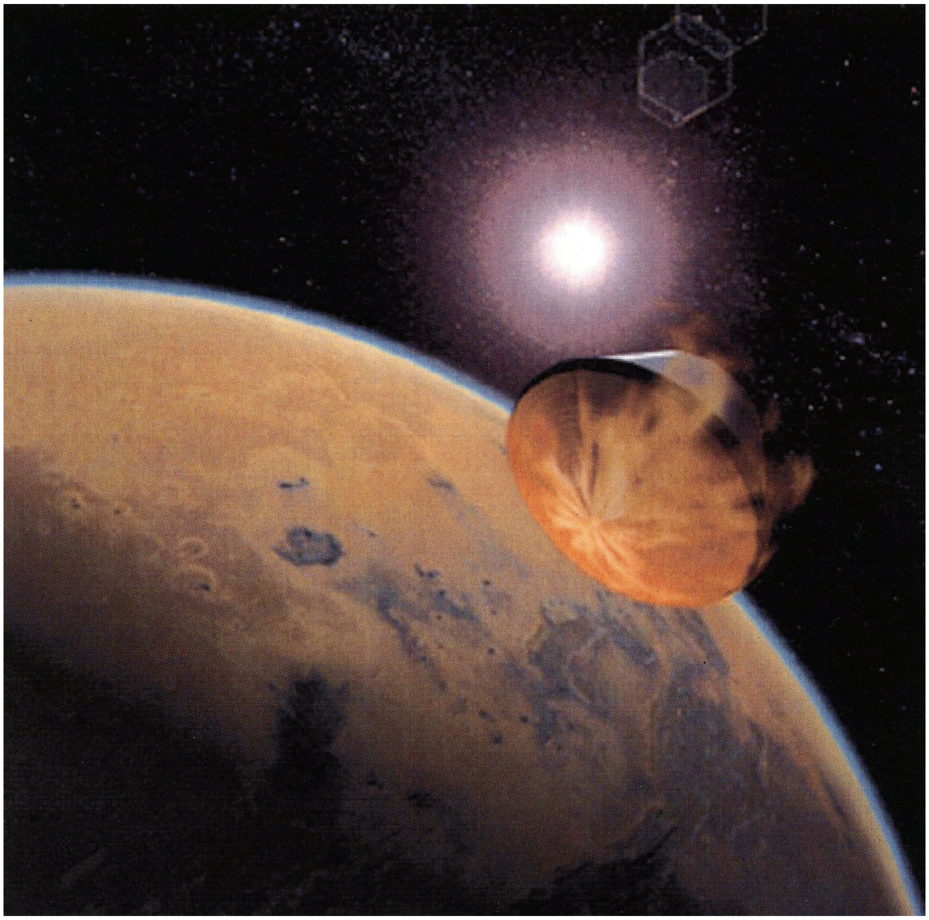
**Nowcasting models** are needed in operational settings to understand events and anomalies. These models must assimilate very recent data to establish the conditions appropriate for the situation encountered.

**Predictive models** are needed for planning future operational activities. Spacecraft operators and some ground system operators need warning about natural events so that they can, for example, make decisions about the operation of their assets.

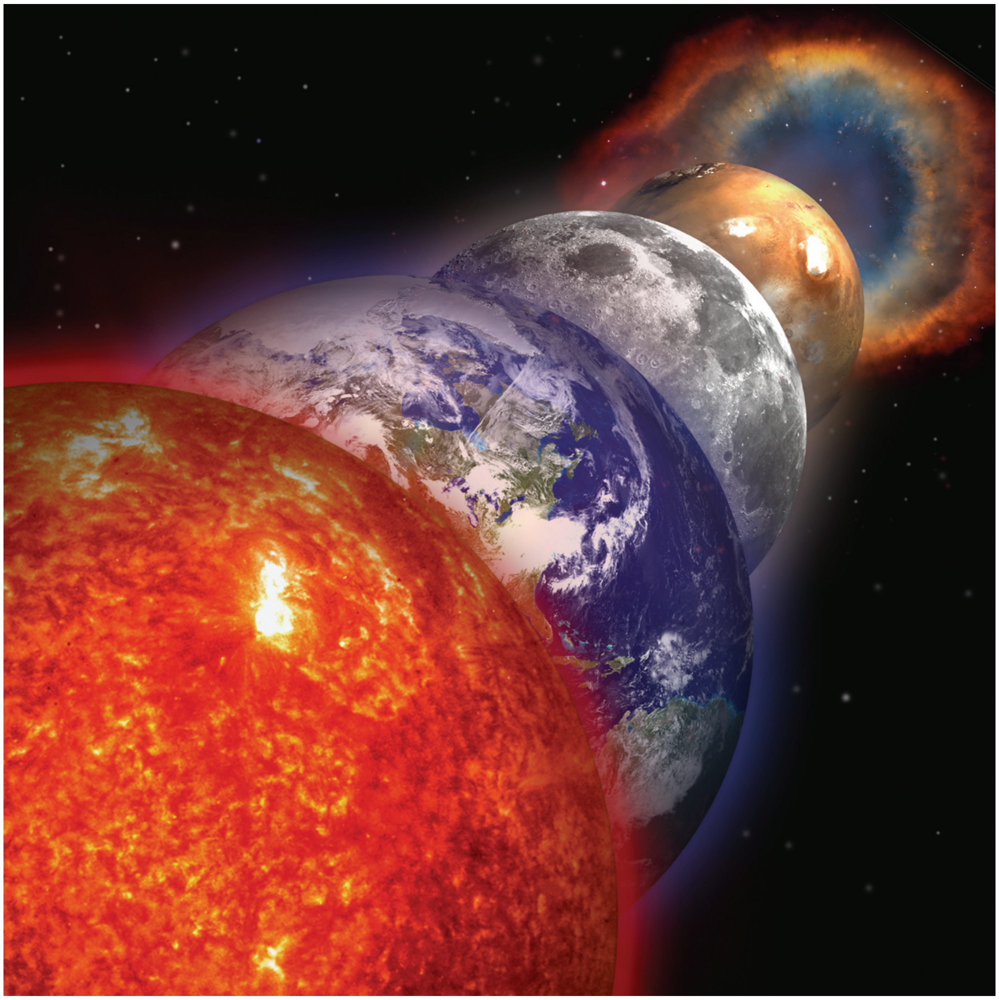
The LWS Geospace Program's design was planned around the need to better understand the outer space conditions that most affect technology and society. The planned LWS Geospace measurements, combined with theoretical model and data assimilative model development, are crucial to the success of the national effort to greatly improve space weather services. They will also be the foundation and provide the testbed of future nowcast and forecast operational models that are being developed for Mars.



Energetic particles in the Earth's inner magnetosphere can have significant impacts on Earth-orbiting satellite systems.



Artist's conception of a spacecraft using aerocapture to enter orbit around  Mars.



Sun, Earth, Moon, Mars, and Beyond... The LWS Geospace Program will play its part in ensuring the safety of future exploration missions.

# 9. Looking Forward

*The LWS Geospace Program was Designed to Fill a Gap in the Nation's Space Weather Program and is therefore Well Aligned with the Nation's New Vision for Space Exploration to Advance Scientific, Security, and Economic Interests.*

As human reliance on advanced technology increases, predicting and mitigating space weather effects becomes an increasingly important national priority. The LWS Geospace program was established **to fill a strategic gap** in the nation's space weather program by providing:

• the statistical data bases needed for the development of the specification and empirical models used by developers of technology, and

• the data sets critical for determining the physical mechanisms that dominate under various space weather conditions. This knowledge will lead to the development of physics-based models used for predictions.

As a result the LWS Geospace program finds itself well-aligned with the nation's new **Vision for Space Exploration**, which focuses on understanding the history of the planets and the search for habitable environments within the solar system. The expected planned and robotic missions to our neighbors in the solar system will likely require staging and technology development activities within the near-Earth environment. During these periods, spacecraft and astronauts will be subjected to serious harm from penetrating radiation. Geospace is the one region in space where we can make the extensive multipoint observations needed to test our understanding of the fundamental processes that generate such radiation.

Furthermore, astronauts and spacecraft reaching the other planets will encounter environments in which fundamental physical processes analogous to those at Earth operate. For example, strong magnetic fields shield some regions of the Martian atmosphere from the solar wind, but may also interact with the interplanetary magnetic field to generate bursts of charged particles. Spacecraft entering orbit or landing on Mars may employ aerobraking within the Martian ionosphere. With suitable adjustment to local conditions, the models developed to understand these space weather effects within Geospace can be employed to help plan missions to the other planets.

The fulfillment of the needs of the user community, of which the new Vision for Space Exploration is a part, by the LWS Geospace program will be an ongoing activity over the next couple of decades, at least. This fulfillment requires two kinds of research: one, **targeted research** to obtain the empirical information needed to characterize the relevant environments, and two, **basic research** to understand the fundamental physics of the solar/planetary system from which physics-based models will be developed to provide forecasting capabilities. Due to the long lead time for implementing missions, performing the data analysis, and developing the needed models, plus the up-front needs by any design community, these research activities must be a sustained activity that is carefully planned and timely implemented. Only with this approach can the needs that are fed into the user community be met. In the process of filling the strategic gap this research will lead to further understanding of the history of our solar system and to unraveling the temporal history of planetary environments that lead to habitability.

# Appendix A: LWS Geospace Program Strategic Objectives

| LWS/Space Weather Effect | | |
|---|---|---|
| **Satellite Systems** | The capability to monitor and predict energetic electron and ion exposure is needed for diagnosis of satellite anomalies and consideration during spacecraft design. (LWS program goal ranking 4) | **A** |
| **Nav/Com/ Rad Systems** | The spatial distribution of electron density in the ionosphere is the key environmental parameter impacting NavComRad systems. (LWS program goal ranking 3) | **B** |
| **Human Flight** | The capability to monitor and predict energetic electron and ion exposure is needed to ensure the safety of astronauts in Earth orbit and of flight crews of high-altitude aircraft. (LWS program goal ranking 2) | **C** |
| **Satellite Drag** | Neutral density is the key environmental parameter determining satellite drag. (LWS program goal ranking 5) | **D** |
| **Ground Systems** | Enhanced ionospheric currents during geomagnetic storms induce currents in ground-level conductors. (LWS program goal ranking 6) | **E** |
| **Global Climate Change** | The effect of solar variability on ozone distribution and on near-surface temperature change must be characterized. (LWS program goal ranking 1) | **F** |

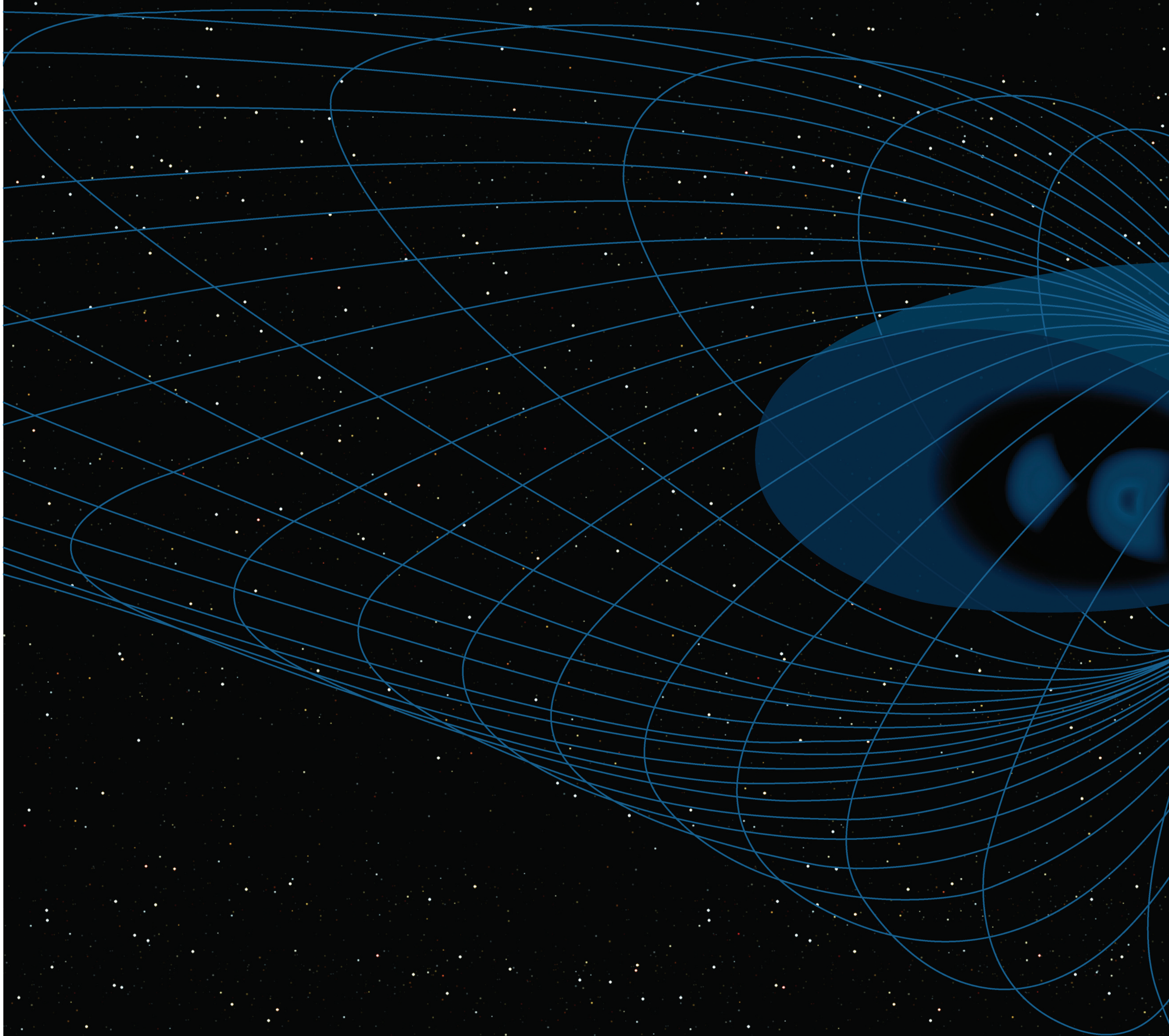
| | LWS/Geospace General Objective: |
|---|---|
| **A C** | **Priority 1:** Understand the acceleration, global distribution, and variability of energetic electrons and ions in the inner magnetosphere**.** SAT report: WG1-5 and 6, WG2-4 |
| **B E** | **Priority 2A:** Determine the effects of long- and short-term variability of the Sun on the global-scale behavior of the ionospheric electron density. SAT report: WG1-1, WG2-1 |
| **B** | **Priority 2B:** Determine the solar and geospace causes of small-scale ionospheric density irregularities in the 100 to 1000 km altitude range. SAT report: WG1-2, WG2-2 |
| **C D** | **Priority 3A:** Determine the effects of solar and geospace variability on the atmosphere enabling an improved specification of the neutral density in the thermosphere. SAT report: WG1-3, WG2-3 |
| **B D E** | **Priority 3B:** Understand how solar variability and the geospace response determine the distribution of electric currents that connect the magnetosphere to the ionosphere. SAT report: WG1-4, WG2-5 |
| **A B C F** | **Priority 4:** Determine the quantitative relationship between very energetic electron and ion fluxes in the interplanetary medium and their fluxes at low altitude, particularly the geomagnetic cutoffs. SAT report: WG1-9, WG2-6 |
| **F** | **Priority 5:** Quantify the geospace drivers that potentially affect ozone and climate. SAT report: WG2-8 |

# Appendix A: LWS Geospace Program Strategic Objectives (continued)

| LWS/Geospace General Objective: | Specific Objectives: |
|---|---|
| **Priority 1**: Understand the acceleration, global distribution, and variability of energetic electrons and ions in the inner magnetosphere.<br>SAT report: WG1-5 and 6, WG2-4 | **Priority 1:**<br>**1.1***:* Differentiate among competing processes affecting the acceleration and transport of outer radiation belt electrons.<br><br>**Priority 2:**<br>**1.2a***:* Differentiate among competing processes affecting precipitation and loss of outer radiation belt electrons.<br><br>**1.2b***:* Understand the creation and decay of new electron radiation belts.<br><br>**1.2c***:* Develop and validate physics-based data assimilation and specification models of outer radiation belt electrons.<br><br>**Priority 3:**<br>**1.3a***:* Understand the role of "seed" or source populations for relativistic electron events.<br><br>**1.3b***:* Quantify the relative contribution of adiabatic and nonadiabatic processes on energetic electrons.<br><br>**1.3c***:* Understand the effects of the ring current and other storm phenomena on radiation belt electrons and ions.<br><br>**Priority 4:**<br>**1.4a***:* Understand how and why the ring current and associated phenomena vary during storms.<br><br>**1.4b**: Develop and validate physics-based and specification models of inner belt protons for solar cycle time scales. |
| **Priority 2A**: Determine the effects of long- and short-term variability of the Sun on the global-scale behavior of the ionospheric electron density.<br>SAT report: WG1-1, WG2-1 | **Priority 1:**<br>**2A.1a***:* Quantify the relationship between the magnitude and variability of the solar spectral irradiance and the global electron density.<br><br>**2A.1b**: Quantify the effects of geomagnetic storms on the electron density.<br><br>**Priority 2:**<br>**2A.2***:* Quantify how the interaction between the neutral atmosphere and the ionosphere affects the distribution of ionospheric plasma.<br><br>**Priority 3:**<br>**2A.3***:* Discover the origin and nature of propagating disturbances in the ionosphere. |
| **Priority 2B**: Determine the solar and geospace causes of small-scale ionospheric density irregularities in the 100 to 1000 km altitude range.<br>SAT report: WG1-2, WG2-2 | **Priority 1:**<br>**2B.1***:* Characterize and understand the origin and evolution of newly-discovered storm-time mid-latitude ionospheric irregularities.<br><br>**Priority 2:**<br>**2B.2a***:* Understand the conditions leading to the formation of equatorial spread-F irregularities, and their location, magnitude and spatial and temporal evolution.<br><br>**2B.2b**: Understand the conditions leading to the formation of polar patches and their high-latitude irregularities.<br><br>**Priority 3:**<br>**2B.3***:* Enable prediction of the onset, location, and development of E-region irregularities. |
| **Priority 3A**: Determine the effects of solar and geospace variability on the atmosphere enabling an improved specification of the neutral density in the thermosphere.<br>SAT report: WG1-3, WG2-3 | **Priority 1:**<br>**3A.1a***:* Determine the variability in the neutral atmosphere attributable to the solar EUV spectral irradiance.<br><br>**3A.1b**: Determine the variability in the neutral atmosphere attributable to magnetospheric inputs.<br><br>**Priority 2:**<br>**3A.2***:* Determine the variability in the neutral atmosphere attributable to internal processes.<br><br>**Priority 3:**<br>**3A.3***:* Determine the variability in the neutral atmosphere attributable to atmospheric waves from below. |

# Appendix B: Acronyms

| | |
|---|---|
| C/NOFS | Communications/Navigation Outage Forecast System |
| DoD | Department of Defense |
| DoE | Department of Energy |
| DoI | Department of the Interior |
| DoT | Department of Transportation |
| EUV | Extreme Ultraviolet |
| EVE | Extreme Ultraviolet Variability Experiment |
| GAIM | Global Assimilation of Ionospheric Measurements |
| GPS | Global Positioning System |
| ITSP | Ionosphere Thermosphere Storm Probes |
| NOAA | National Oceanic and Atmospheric Administration |
| NPOESS | National Polar-orbiting Operational Environmental Satellite System |
| NSF | National Science Foundation |
| RBSP | Radiation Belt Storm Probes |
| SDO | Solar Dynamics Observatory |
| SNOE | Student Nitric Oxide Explorer |
| STEREO | Solar Terrestrial Relations Observatory |
| TEC | Total Electron Content |
| TIMED | Thermosphere Ionosphere Mesosphere Energetics and Dynamics |
| TR&T | Targeted Research and Technology |



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